PLANFORM EVOLUTION MODEL FOR THE MIDDLE RIO GRANDE, NM

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Abstract

First documented in the 1500s by Spanish explorers, large floods played a significant role shaping the Rio Grande in New Mexico. These floods created periods of punctuated channel evolution that not only rapidly aggraded the river corridor but also caused large-scale channel shifts. Construction of dams, levees and maintained floodways in the watershed concurrent with natural changes in precipitation, runoff, and sediment supply resulted in a reduction in flood magnitudes and frequencies, and changes in channel and floodplain morphology. With the Rio Grande's flooding and aggradation subsiding, there came a change in the channel's evolutionary process towards a river with a more systematic pattern of change, especially in the Middle Rio Grande (MRG), Cochiti Dam to Elephant Butte Dam. As a first step towards predicting future changes based on the reduced hydrology and sediment regime, an empirically based planform model is proposed that describes two sequences of planform evolution found throughout the MRG. Although changes in the planforms initially appear similar throughout the study area (first three stages of the model), planform evolution splits into two distinct tracks after the channel begins abandoning medial and point bars located within the active channel (Stage 4). At this point the relative sediment transport capacity becomes a deciding factor in the channel's future form: those channels that are deficient in transport capacity remain deficient in capacity throughout their evolution, while those channels that have excess capacity actively shape their channels by eroding the channel bed and banks. Channels that are deficient in transport capacity evolve towards avulsion while the channels that have excess sediment transport capabilities evolve towards a migrating bend planform. Average channel slope is used as an initial description of a reach's transport capacity, such that less steep reaches tend toward channel filling and avulsion events while relatively steeper reaches tend toward a migration pattern. Cycling through either of the sequences is ongoing, however to return to Stage 1 appears to require a channel re-setting event such as a large influx of sediment or exceptional flood. Since local influences and initial boundary conditions vary throughout the MRG, a 160 mile reach, all stages in this conceptual model are currently represented.

INTRODUCTION

First documented in the 1500s by Spanish explorers, large floods played a significant role on the Rio Grande in New Mexico, creating periods of punctuated channel evolution with avulsions, migrations and other large-scale channel shifts (Scurlock 1998). So big were these floods and shifts that the Spanish simply named this river the "grand river". As communities began to develop along this wandering river corridor, desires to control the system became paramount. Initially, small diversion dams, levees, and channelization projects were implemented to protect local communities (Scurlock 1998), however these proved inadequate. Starting in the 1950s, construction of several large dams in the watershed (Lagasse 1980, Massong and Porter 2004) concurrent with natural changes in precipitation, runoff, and sediment supply (Leopold 1951, Gutzler 2000, and Molnar and Ramirez 2001) resulted in a reduction in flood magnitudes and frequencies, with the last large flood occurring in 1942.

With the Rio Grande's flooding and aggradation subsiding, there came a change in the channel's evolutionary process towards a river with a more systematic pattern of change, especially in the middle Rio Grande reach (MRG), from Cochiti Dam to Elephant Butte Dam (Figure 1).

Initially, the Rio Grande's channel simply shrank through general abandonment of side-channels and wider bends (Makar et al. 2006, and Richard and Julien 2003) in the 1930s and 1940s. Then large-scale construction of a more efficient floodway with controlled banklines in the 1950s and 1960s again straightened the channel (Tashjian and Massong 2006). Upstream from Elephant Butte, dam construction for water storage and flood protection began on the tributaries then moved to the mainstem Rio Grande. With continued natural and human induced reductions in sediment supply and peak flows, widespread evolution in how the river functions continues today (Ortiz and Meyer 2002, Massong and Porter 2004, Massong et al. 2006, and Makar et al. 2006).

As a first step towards predicting future changes in the MRG based on this continued hydrology and sediment regime, an empirically based planform model is proposed that describes a sequence of planform evolutions found throughout the MRG. Although initial changes in the planforms appear similar throughout the reach, the evolution splits into two distinct tracks after the channel begins abandoning medial and point bars located within the active channel. The planform model is subdivided into relatively steeper reaches that tend toward a bend migration pattern, and the less steep reaches that tend toward channel filling and avulsion events.

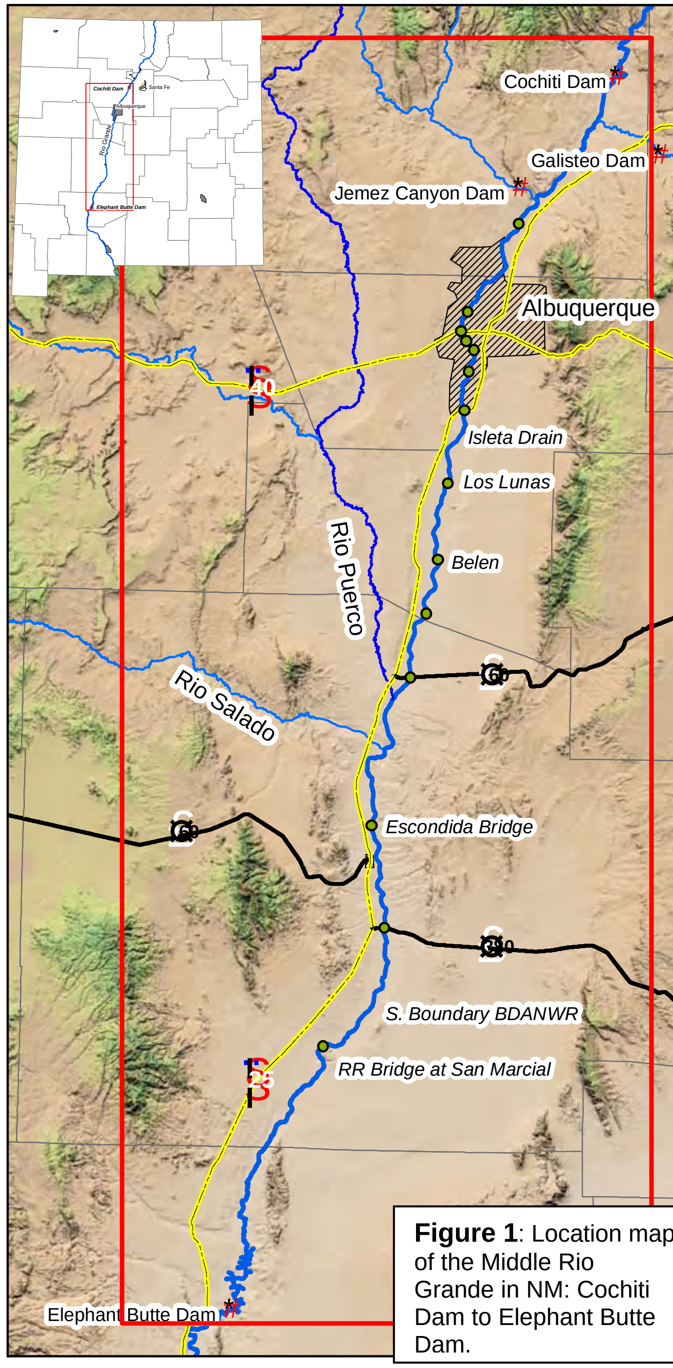

Figure 1: Location map of the Middle Rio Grande in NM: Cochiti Dam to Elephant Butte Dam.

CHANGES IN NATURE

Precipitation and Climate

Leopold (1951) was one of the first to document a climatic change for storm precipitation patterns in New Mexico; using 1850-1950 precipitation data, he showed that although year precipitation totals remained relatively similar through the time period, storm characteristics changed. This study documented a steady increase in the number of small storms (<0.5 inch rainfall) while the large storm events decreased.

Almost as a continuation of Leopold's work, Molnar and Ramirez (2001) assessed rainfall patterns from 1948-1997, but focused their study on patterns in the Rio Puerco watershed. Like in Leopold (1951), Molnar and Ramirez showed a continued increase in the volume and intensity of the small-moderate rain events. However, the later data showed that the yearly number of rainy days continued to increase with a growing number of non-summer rainy days, and there was a significant increase in average-yearly precipitation after the 1940s.

Diaz and Gutzler (*in prep)* document a pattern between summer precipitation and snowpack depths; starting in about 1960, a negative correlation pattern was detected between summer rainfall in New Mexico and the April 1 snowpack over the southern Rocky Mountains. This study found that a year with a poor snow pack was strongly correlated with a wet summer season, such that the yearly precipitation was dominated by winter or summer storms, but not both. This snowpack/rainfall trend reigned for approximately 30 years, 1960-1990, before returning to a more random cycle.

Runoff Patterns

Although Molnar and Ramirez (2001) clearly document an increase in yearly precipitation total, their study also clearly documents a decrease in peak flows in the Rio Puerco watershed. Others have also noted a lack of increase in stream flows during this increasingly wet period throughout the southwest (Wahl 1992, Lettenmaier et al. 1994 and Chiew and McMahon 1996). Just upstream of the MRG are two long-term USGS river gages that have peak flow data dating to prior to 1900. Similarly to Molnar and Ramirez (2001), these data show that almost all of the large peak flows occurred prior to 1942 (Figure 2). These studies and data which describe flow trends throughout New Mexico indicate that current peak flows have decreased from the large, historical peak flows and that this trend is regional.

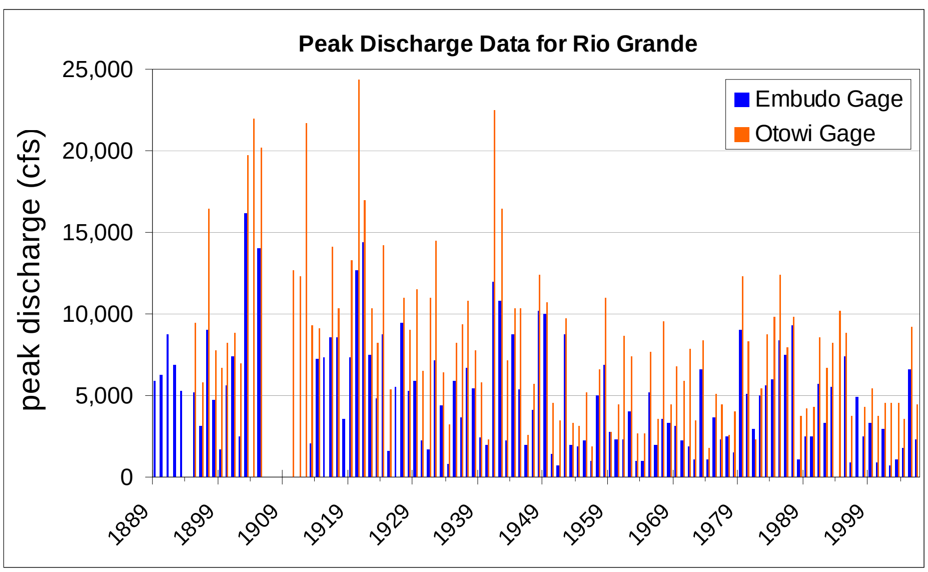

Figure 2: Instantaneous flows on the USGS Rio Grande at Embudo, NM gage, 1889-2006 (Sta # 08279500), and USGS Rio Grande at Otowi, NM gage, 1895-2006 (Sta # 08313000). **Note**: Some of the reduced peak flow magnitude on the Rio Grande at Otowi gage is due to several large water storage and flood control dams on a main tributary-Rio Chama.

Patterns in Sediment Supply

The supply of sediment to the Rio Grande is at best episodic, depending greatly on both delivery of sediment by the tributaries and remobilization of stored sediments in the channel and floodplain. These cyclic sedimentation rates have been studied for several decades, predominantly on the Rio Puerco, a main tributary of the MRG (Bryan 1928, Bailey 1935, Happ 1948, Nordin 1963, Love 1986, Gorbach et al. 1996, Love 1997, Gellis 2002), but throughout the area (Miller and Wendorf, 1958, Gellis 1992, Klinger and Klawon 2003 Gellis et al. 2003). Three valley fill/scour cycles have been documented in this area that date back an estimated 3,000 years (Klinger and Klawon 2003, and Gellis et al. 2003) with the last erosion/scour cycle ending in about the 1950s.

The most recent fill/scour sequence of the tributaries was well document in the Rio Puerco watershed in the late 1800s to early 1900s. Starting sometime in the 1800s, arroyos throughout the MRG basin were incising and delivering enormous loads of sediment to the MRG (Gellis 1992). By the 1950s, most of the incision had already occurred in the MRG tributaries and the tributary channels had begun to stabilize. With arroyo channel stabilization came a naturally decreasing sediment load to the Rio Grande (Gellis 1992, and Gorbach et al. 1996). Other studies in the region collaborate that the supply of sediment transported through the arroyo network is also decreasing from those high historic levels (Love 1997, Gellis 2002, and Gellis et al. 2003). In fact, findings on headwater tributaries in the Rio Puerco watershed (Gellis 2002) indicate that some small waterways are now starting to re-fill, hence storing the sediment close to its source in the headwaters rather than transporting it downstream to the Rio Grande. This evolution of the arroyos/tributaries towards storage of sediment rather than rapid transport is naturally decreasing the supply of sediment to the MRG and is expected to continue into the near future.

HUMAN ALTERATIONS TO THE MRG

Alterations to the Rio Grande channel are numerous and date back thousands of years with indigenous inhabitants diverting water to irrigate crops. Initially, only small channel modifications occurred, but beginning in the twentieth century, large channel-realignments, miles of levees and jetty fields, numerous diversion dams and large dams were constructed. These modifications were intended to 'tame' the wandering channel and protect nearby inhabitants from the relatively frequent flood events. Unaware of the natural changes in sediment supply and hydrology in this portion of the Rio Grande, the U.S. Congress passed several flood control acts after the last large flood of 1942. Although the flood of 1942 was not the largest flood of record, this flood occurred on the heels of the 1941 flood, which was one of the largest and longest events recorded in the MRG. By 1942, aggradation of the Rio Grande channel in Albuquerque and at several other locations had super-elevated the channel, creating a flood situation whenever the flows increased. Several large dams were constructed within the MRG watershed with the goal of flood peak and sediment load reduction. The most influential of the large dams is Cochiti Dam; located on the mainstem Rio Grande, this dam began operations in 1973. This project and others effectively controls flood flows in the MRG and have captured large volumes of sediment.

EXAMPLES OF THE EVOLVING MIDDLE RIO GRANDE

Many physical aspects evolve within a river as the hydrology and sediment supply change. On the Rio Grande, changes of several features have preceded the planform: rapid channel narrowing (Makar et al 2006), incision (Massong et al. 2006), and bed material coarsening (Lagasse 1980, Ortiz and Meyer 2002, Reclamation 2003, Bauer 2009). These individual in-channel transformations are specific fluvial processes whereas planform is more the appearance of how these processes shape the river's channel and floodplain. Three of the most readily noted and rapid planform changes are: 1-the development of and evolution of medial bars in the Belen, NM area, 2-avulsions downstream from the Refuge, and 3-the development of a migrating channel downstream from the San Acacia Diversion Dam.

Medial Bars in Belen, NM

For many years the Rio Grande between Isleta, NM and the Rio Puerco confluence has been an area regarded as stable and relatively static in processes. Confined by levees with reinforced banklines via jetty jack installation and thick riparian vegetation (Figure 3), this reach maintained stable channel dimensions since the floodway construction in the 1950-1960s.

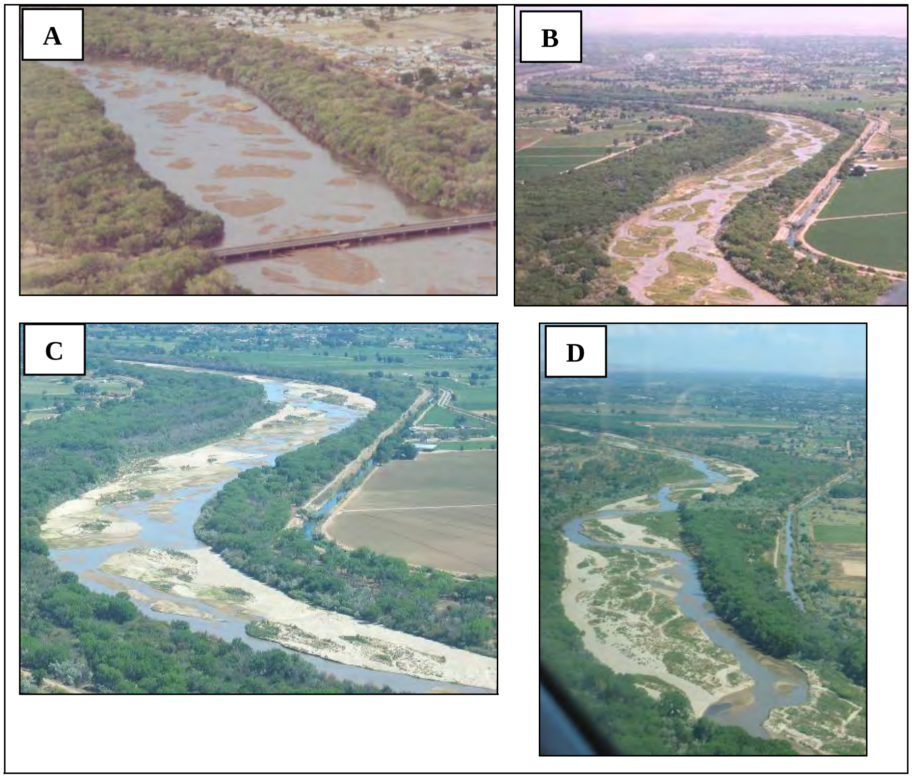

Figure 3: Series of photographs taken near Belen, NM from 2000-2006 showing the rapid adjustment of bankline location as islands emerged and then attached to the bankline. Photo Dates: A=2000, B=2002, C=2005, D=2006.

Prior to 2000, large dune fields composed of sand could be found moving through the active channel at most times of the year with a slightly aggrading channel bed and active floodplain throughout. However, during a recent drought, 1999-2004, downstream transport of the large macro-dunes stalled; encroachment of vegetation was quick as herbaceous vegetation initially covered these bars giving way to saplings within 2 years. Although water was minimal during this time, the woody vegetation grew quickly, creating a stabilized surface prior to the return of more 'normal' flows in 2004. About this same time, 2004, sizeable gravel patches were first noticed covering portions of the channel bed. With an observed sediment load of virtually all sand and silt, finding deposited gravel patches was unexpected. Initial conclusions for the gravel were that the sediment transport character of this reach was evolving as the river was collecting the gravel and then depositing it together in relatively consistent locations.

In 2005, a slightly larger than 50% chance frequency spring flood (a.k.a., a 2-year event) broke the drought cycle, resulting in significant vertical accretion of the medial bars. In many locations, a dominant channel formed as large sections of the formerly active channel partially filled with sediment; also during this process, an obvious thalweg formed in the dominant channel. Gravel patches became more numerous and their locations started to become more predictable: coating the upstream entrance to side channels; piled up along the upstream edges of islands. By 2007, small riffles had begun to form within the main channel. In 2006, several high peak flows occurred again in this reach, but these flows originated from the sediment-laden summer rain storm floods which continued the filling process, reinforcing the narrow dominant channels and further elevating the side channels with sand deposition.

Today, these high flow side channels are rapidly being colonized by vegetation and appear to be converting to floodplains (Figure 3D). The channel dimensions, including width, have greatly changed over this five-year period and more observable gravel deposits are being found. The channel has changed so dramatically in this reach since 1999 that predicting future planforms is a widely disputed topic.

Historical and Recent Avulsions

The village of San Marcial, NM located on the Rio Grande's floodplain just upstream from Elephant Butte Reservoir is the first well documented historical avulsion in the MRG (Scurlock 1998 and Van Citters 2000). Beginning in the early 1900s, several floods inundated the village of San Marcial, NM. The severity of flooding continued to increase into the 1920, culminating in the disastrous flood of 1929. The 1929 flood developed as a set of late-summer, coincident storms on the Rio Puerco, Rio Salado and several other Rio Grande tributaries accumulated an extraordinary high flood flow (an estimated 30,000 cfs was delivered by the Rio Puerco alone). The resulting flood deposited more than 7 feet of sediment in San Marcial, burying many buildings and agricultural fields; essentially destroying the community (Van Citters 2000). Although most of the town's inhabitants vacated the ruined town in 1929, by 1937, the town was completely abandoned after another flood destroyed the last remaining irrigation facilities (Scurlock 1998). Historical aerial photographs (1935) show that the Rio Grande had spread out into large wetland complexes throughout this area, some covering the abandoned town area of San Marcial as a new channel struggled to form. The high deposition rates were initially blamed on its location, as it is located only 8 miles upstream from Elephant Butte Reservoir but later analyses showed loss of access to the floodplain by railroad levees and effects of the San Marcial railroad bridge were more significant (Van Citters 2000).

Figure 4: Rio Grande channel full of sediment in 2005 near railroad bridge at San Marcial.

In 1991, 1995 and 2005, the Rio Grande's channel completely filled-in (a.k.a., plugged) immediately upstream from the historical town of San Marcial (Figure 4). With significantly better data collection and hydraulic and sediment modeling now available, the recent channel-filling process has been correlated with local channel and overbank flooding characteristics (Boroughs 2005, Lai 2009) such as super-elevation of the river channel to its floodplain rather than proximity to Elephant Butte Reservoir. In 2008, another plug formed approximately 10 miles upstream from the 2005 plug location, further supporting the evidence for local physics controlling the channel filling process rather than the Reservoir. In each of these later plugged channel events, the main channels were re-dug when the flows receded, so that the flows were returned to the same channel before new channels on the floodplains could develop. All of these recent near-avulsions have occurred downstream from the US 380 bridge crossing (Figure 1).

Migration Downstream from the San Acacia Diversion Dam

The Rio Grande downstream from the diversion dam at San Acacia, NM to at least Escondida has changed dramatically in the last 50 years, going from an extremely wide (1000 ft+) channel laden with sandy material to a narrow (~250 ft), deeply incised channel with a gravel dominated bed throughout most of the reach (Reclamation 2003, Makar et al. 2006 Massong et al. 2006, and Bauer 2009). This reach's relatively steep channel, at an average of 0.0012 ft/ft, is second in the MRG only to the steep channel immediately downstream from Cochiti Dam.

The changes in channel width (Makar et al. 2006) and instigation of channel incision (Massong et al. 2006) were greatly influenced by the channelization activities in the 1930s-1960s, as large bends were disconnected and the channel was straightened. During and since this timeframe, Makar et al. (2006)

documented an ongoing reduction in channel width with a recent rapid narrowing of the non-vegetated channel between the 1980s and 2002. As in other sections of the Rio Grande (e.g., Belen Reach), this episode of narrowing was associated with the stabilization of bar sediments. However, unlike other reaches of the Rio Grande, while the bars were stabilizing, the channel bed rapidly incised an estimate 4 feet (Massong et al. 2006). After the incision, the channel bed material coarsened from sand to extensive patches of gravel-sized particles. The growing concentration of gravel transporting into the reach was first recorded in routine USGS bed material samples collected at the Rio Grande at San Acacia, NM in the late 1980s (Figure 5). Coherent patches of gravel on the channel were not documented until 2000, when an extensive bed material survey was completed (Reclamation 2003). Although the channel bed is now gravel dominated, these larger sediments are often covered by thick sand dunes that still migrate through the reach.

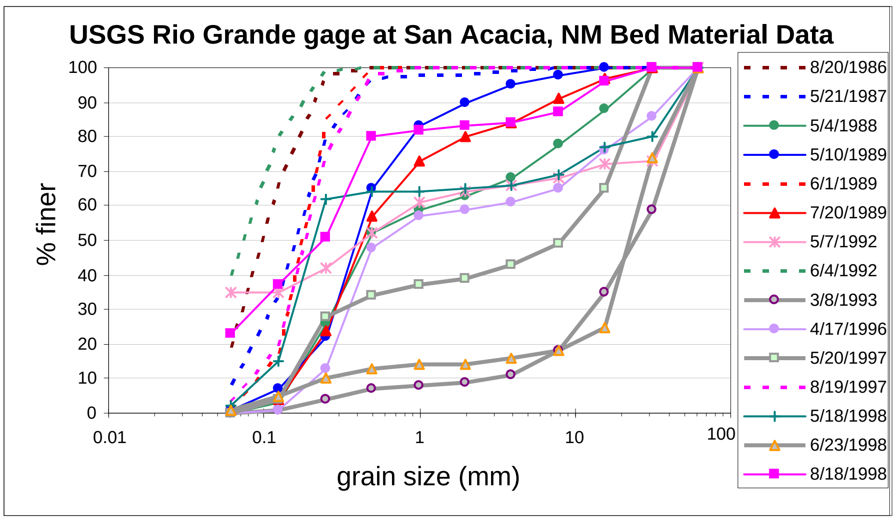

Figure 5: Selected bed material data from samples collected at the USGS Rio Grande gage at San Acacia, NM (1966-1998). The dotted curves represent samples composed entirely of sand (<2mm), while the other lines represent sediment samples with some gravel component. Note: Samples represent the bed surface at the time of sample, no attempts would have been made to sample gravel deposits existing under sand dune deposits.

Combined, these three changes (narrowing, incising and sediment coarsening) altered how the Rio Grande functions in this section of the MRG. The narrowing channel coupled with incision has created a deeper channel throughout this reach. With the high incision, the historical floodplains are now acting as terraces and less of the flood flows are leaving the active channel, creating deeper flows during normal events. In combination with these hydraulic changes and the naturally decreasing supply of sediment, the emergence of the gravel-bed is predictable. The gravel material adds stability to the channel bed during the non-channel forming flows, which essentially further reduces the channel's supply of sediment as it no longer can erode the bed during this smaller flows. In conjunction with the changing bed stability, an alternating thalweg has recently formed, an unusual feature in the MRG. The emergence of the thalweg has changed the transport processes of water and sediment to a much more efficient system. The incision of the channel bed also lowers the newly emerged thalweg location, such that it intersects the bank material underneath the riparian root zone setting-up the final piece needed for migration. This highly efficient channel has a transport capacity that exceeds the available sediment, and is now re-activating the bank/terrace materials. Without the root mass to provide solidity to the bank material which consists primarily of "sugar sand", bank erosion has become widespread throughout this reach.

In the late 1990s, the Rio Grande began forming migrating bends downstream from San Acacia Diversion Dam (Figure 6); ensuing monitoring documented detailed migration characteristics on several bend sequences. By 2005, the bends were not only large and grouped with multiple bends in series, but eroded bank material was measurable in terms of acres at some of the bends.

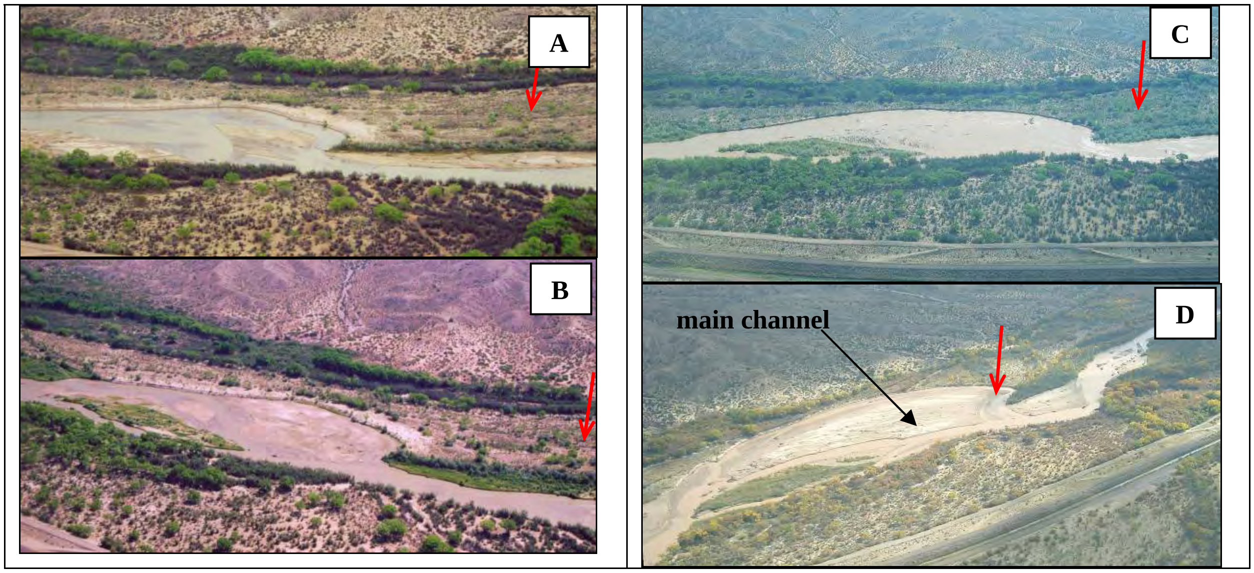

Figure 6: Laterally migrating bend located about six miles downstream from San Acacia diversion dam. Bend initially formed in 1998/1999 as a small bankline scallop, rapidly grown in 2004-2006, in 2006 a second cutoff channel formed that began to carry more flow that the main channel along the outside bankline, by summer of 2007, the cutoff channel becomes the main channel such that the outside channel's bankline has begun stabilizing. Red arroyos identify the same location in each photograph. Photo Dates: A=2000, B=2002, C=2005, D=2006.

The evolution of the bends follow a similar pattern: 1-a small scallop forms in the bank and grows laterally in both the upstream and downstream directions, 2-the bend begins to predominantly erode in the downstream direction, sometimes with a distinct hook shape forming (Figure 6A) while a point bar forms on the inside of the bend, 3-as the bend continues to grow and migrate both downstream and laterally, the bar grows and a side channel cuts through the inside of the bar (Figure 6B); 4-the side channel's bed incises, becoming the main channel while the channel along the outside the bend becomes less active (Figure 6D); and 5-the channel along the outside of the bend becomes abandoned. Surprisingly, the sequence from bend formation through migration to bend abandonment can be rapid in this reach, with an elapsed timeframe of <10 years at the bend in Figure 6.

PLANFORM EVOLUTION MODELS

Generally the Rio Grande's channel throughout the middle section is changing due a variety of influences; even though the initial channel changes were a simple ubiquitous narrowing, we recently have been able to discern two distinct tracks of change that although subtle in the beginning, lead in two distinct directions that create channels that are nearly opposite in function. The defining process dividing these two tracks is the channel's relative sediment transport capacity: those channels that are deficient in transport capacity remain deficient in capacity throughout their evolution, while those channels that have excess capacity actively re-activate stored sediments by eroding the channel bed and banks.

Based on many observations throughout the MRG, review of the current and historical sediment and hydrology patterns, research into causes and events leading up to large changes in the Rio Grande's channel (both human caused and natural), a conceptual model was created to describe the sequences of evolution (Figure 7) that are currently ongoing. The first three stages are common throughout the MRG and represent the planforms as the active channel narrowed. Only as Stage 3 ends does the relative sediment transport capacity become a deciding factor in the channel's future form. Channels that are deficient in transport capacity evolve towards avulsion after Stage 3, where the channel aggrades, becoming super-elevated until eventually the main flow shifts onto the lower elevation floodplains and forms a new channel (Stages A4-A6). Channels that have excess sediment transport capacity evolve towards a migrating bend planform where the channel bed and bank material are eroded both laterally and vertically (Stages M4-M8). Cycling through either the A4-A6 stages or the M4-M8 stages appears to be ongoing, however to return to Stage 1 requires a channel re-setting event such as either a large influx of sediment or an exceptional flood. Since local influences and initial boundary conditions vary throughout the MRG, all stages in this conceptual model are currently represented in this 160 mile reach.

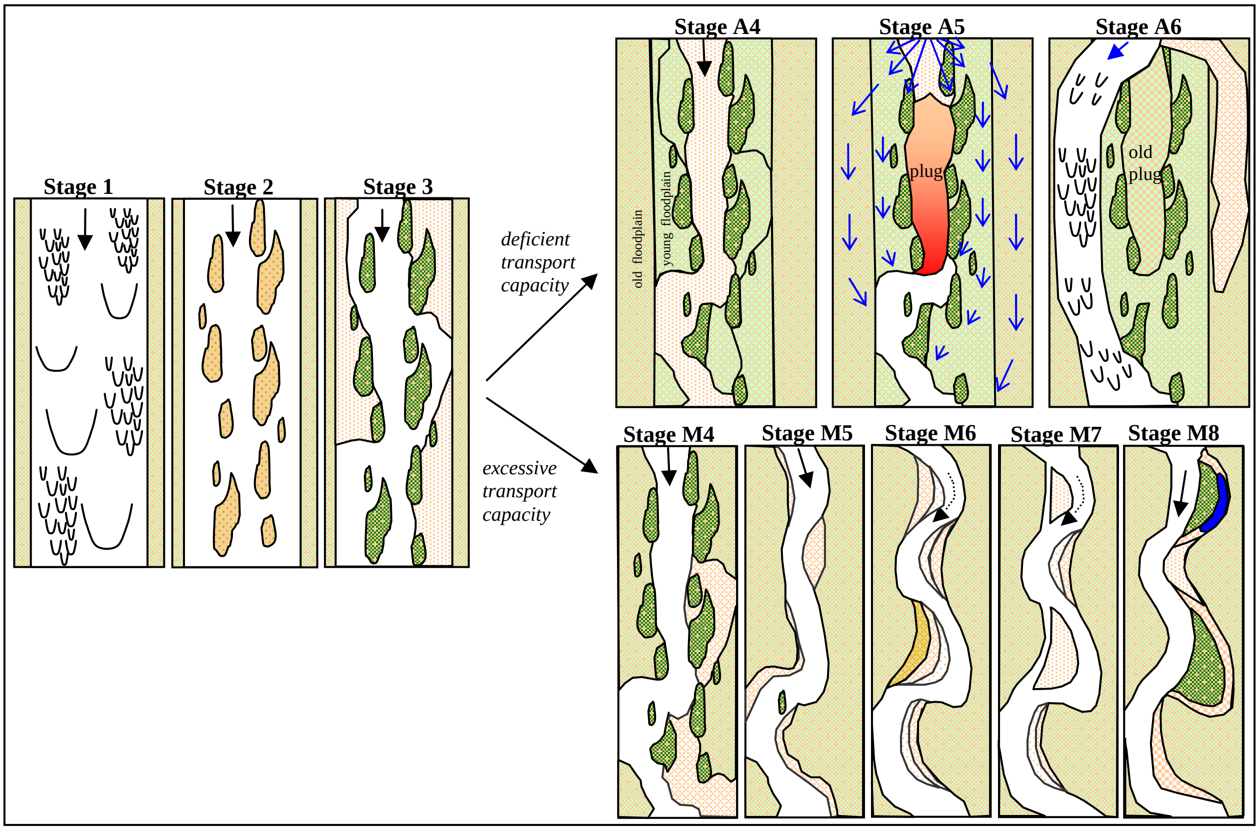

Figure 7: Sequence of planforms with the bifurcation beginning after Stage 3 where the channel's relative sediment transport capacity determines future planforms: deficient capacity channels aggrade with potential avulsions (Stages A4-A6), while excess capacity channels migrate (Stages M4-M8).

Initial Stages

Stage 1 encompasses the large channels that have a sufficiently high sediment load and large floods such that a wide main channel, free of vegetation is maintained. These channels form a single channel during high flows usually with a connected floodplain but become braided during most of the year as the discharge decreases. During the low-flow seasons, the flow is relatively shallow across the channel, without a well defined thalweg. Bed material is composed mostly of sand with some gravel which is readily transported during most flows in the form of dunes and macro-dunes. The floodplain is connected, and the channel bed elevation is either stable or slightly aggrading. The banklines may or may not be stable, but the key factor is that the channel bed, bars, and dunes are active enough to prevent vegetation encroachment. This stage is the traditional description of the Rio Grande.

Stages 2-3 describe the evolution of active sand dunes to islands and bars that act like floodplains. In these two stages the key change is that the sand dunes from Stage 1 start to stabilize, first through a temporary change in the flood hydrology which evolves into stabilization by vegetation regardless of flow. The transition from Stage 1 to Stage 2 occurred through most of the MRG during the latest drought of 1999-2004. This was 5 years in which virtually no spring or summer floods occurred, and extensive portions of the Rio Grande's channel dried during the summer months (main growing season). Vegetation encroachment was rapid in this 5-year period (Figure 3). When normal flows returned in 2005, the water found a completely altered channel, with numerous islands blocking significant portions of the active channel. Although the flow was high enough to inundate these islands, and some were eroded away, the vast majority of them survived the flood and the vegetation flourished. With the thick stands of saplings, most islands rapidly aggraded in 2005, which served to only reinforce them in the following year's spring flood. As additional floods occur, the islands become attached to the banklines as sediment deposits between the islands the bars. Stage 2 is specifically the development of the islands which macro-dunes (medial bars) temporarily freeze long enough for vegetation to colonize. The islands force a split in the flow creating an anastomosing network. As the vegetation continues to improve stability of the island surface, they transform into floodplain-like surfaces, Stage 3; significant vertical accretion of these surfaces may occur during high flows.

Stages of the Aggrading Reach

In reaches of the MRG where the sediment load is close to or exceeds the transport capacity of the river's main channel, the transition from Stage 3 to Stage A4 is ongoing and may not even be discrete in time as channel filling may be already ongoing in Stage 3. In Stage A4, the floodplain becomes or remains connected at moderate flows as the main channel continues to fill. Although the floodplain and islands are also vertically accreting in this stage, the main channel is accreting faster and becomes super-elevated over its floodplain.

Aggradation rates for channels in Stage A5 are rapid as the channel filling begins to plug the entire channel to the tops of the banks. At this stage, eventually all flow of the river is shed onto the floodplains in. Although the downstream conveyance of water is relatively slow on the floodplain, the conveyance of sediment is even slower and readily deposits in the floodplain. As the floodplain fills with coarser sediments, a dominant, new channel forms, Stage A6. The new channel by-passes the old plugged channel, but does not efficiently transport water and sediment until the new channel is well-formed with deep enough banks to convey moderate sized flows, creating a full avulsion.

Stages of the Migrating Reach

Although Stages A4 and M4 might look similar from the air, Stage M4 is distinctly different in that the transport capacity in this channel exceeds the incoming sediment. Rather than the channel filling and getting smaller as occurs in Stage A4, in Stage M4 the channel vertically erodes and increases its channel size. This incision also helps to establish a dominant channel while the other channels convert temporarily into high-flow channels before switching to floodplains. In this stage, vegetation encroaches into these less active side channels as they continue to be abandoned and evolve toward floodplain surfaces. Also with the increased channel depth, grain sorting begins as the sediment transport processes change from dune migration into a more selective transport process; limited gravel armoring has been observed in this stage as the main channel captures all of the flow.

In Stage M5, the channel bed continues to scour until either the bed material coarsens sufficiently to protect the bed from erosion or the channel reaches some sort of stable slope where the stream's available energy to transport sediment is relatively equal to the sediment supply. The general appearance of the channel is a single-threaded, slightly sinuous, main channel. Stage M5 can be a short-lived stage (a few years) or a final stage depending on how quickly the armoring occurs or if the stable slope is attained easily.

For those channels that are not trapped in Stage M5, they continue to incise until the unprotected bank material below the riparian root zone begins to erode as well, Stage M6. These channels have steep slopes which efficiently transport sediment and water in a well-formed alternating thalweg. As the migrating pattern forms, prominent point bars develop on the inside of the bends, further enhancing the lateral migration pattern.

In nearly all of the active bends monitored on the MRG, a side channel cuts through the point bar that developed at the bend, Stage M7. Although this side channel is initially small, it begins to convey increased amounts of water, until eventually it captures the main flow (Figure 6D). This new main channel grows in size until it can also convey all of the water and sediment during the common higher events, which allows the old channel to fully abandon, vegetate and begin functioning as a floodplain, Stage M8. Migrating bends can transform quickly from Stage M6 to Stage M8.

SLOPE AS A PLANFORM SEQUENCE INDICATION

Although the governing processes are different, each of these planform evolutionary tracks can lead to shifts in the channel's location through either migration or avulsions, events in the MRG that have been relatively well documented since the 1500s. Comparisons between historical and recent channel shifts and reach-length channel slopes found that avulsions and migration occurred in distinctly different locations throughout the MRG, and that they coincided with general patterns in channel slope. The locations dominated by avulsion processes occurred in areas where the reach slopes were less than 0.0007 ft/ft, while channels that migrate have average channel slopes larger than 0.0009 ft/ft (Figure 8).

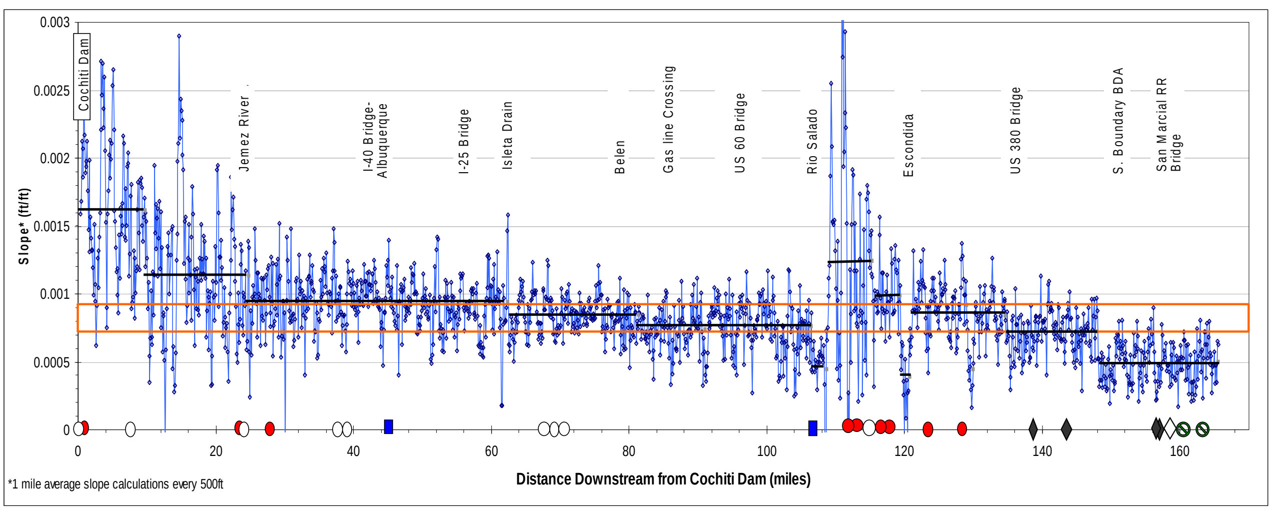

Figure 8: Average channel bed slopes (2002) from Cochiti Dam to the Elephant Butte Reservoir. Slopes are calculated from mean bed cross sectional elevations for 1 mile reaches with a measurement about every 500 feet. Red dots=recent channel migration, green-slashed dots=migrations associated with rapid bed incision, white dots= historical records of migration (>20yrs old). Grey diamonds=recent channel plugs/attempted avulsions, white diamond=historical avulsion at San Marcial, NM. Blue rectangles=migration occurred in combination with rapid channel bed deposition. The orange box represents channel slopes where migration and rapid channel bed deposition processes mix, forming a transition zone such that the dominant process may be either migration, aggradation or a combination of the two processes. The historical channel shifting information is summarized from Scurlock (1998). Data for the recent migration and avulsion events have been observed and documented by the authors in various Bureau of Reclamation-Albuquerque Area Office reports.

For channels with reach average slopes between 0.0007-0.0009 ft/ft, it is unclear if one process dominates; it is presumed that probably either process could occur in these intermediately sloped channels. However, in the complex world of the Rio Grande, it is also possible and likely that these channels could evolve with an interestingly complex combination of both avulsions and migrations.

REFERENCES

Bauer, T. (2009). "Evolution of Sediment on the Middle Rio Grande, NM". Sedimentation and River Hydraulics Group, Technical Service Center, Bureau of Reclamation, United States Department of the Interior, Denver CO.

Boroughs, C. B. (2005). "Sediment Plug Computer Modeling Study, Tiffany Junction Reach, Middle Rio Grande Project, Upper Colorado Region". U.S. Department of the Interior, Bureau of Reclamation, Albuquerque Area Office. Technical Report, Oct 2005, p. 122.

Chiew, F.H.S., and McMahon, T.A. (1996). "Trends in historical stream flow records, Regional Hydrological Response to Climate Change", J.A.A. Jones et al., Ed., Kluwer Academic, p 63-68.

Gellis, A.C. (1992). "Decreasing trends of suspended sediment concentrations of selected streamflow stations in New Mexico", Proceedings of the 36th annual New Mexico water conference- agencies and science working for the future, p.77-93, New Mexico Water Resources Research Institute Report 265.

Gellis, A.C. (2002). "Twentieth Century Arroyo Changes in Chaco Culture National Historical Park", U.S. Geological Survey Water-Resources Investigations Report 01-4251, 42p.

Gellis A.C., Pavich, M., and Aby, S. (2003). "Sediment Budget for Two Semi-Arid Watersheds, Rio Puerco Basin, New Mexico", Geological Society of America Abstracts with Programs, Paper No. 26-4.

Gorbach, C., Love, D., Piper, S., Davis, R., and Cross, A. (1996). "Rio Puerco sedimentation and water quality study: Preliminary findings report", U.S. Department of the Interior, Bureau of Reclamation Albuquerque Area Office, 102 p.

Gutzler, D.S. (2000). "Covariability of Spring Snowpack and Summer Rainfall across the Southwest United States", Journal of Climate, American Meteorological Society, Vol. 13, pp 4018-4027.

Klinger, R.E., and Klawon, J.E. (2003). "Late Holocene Alluvial Stratigraphy and Geomorphology of the Little Colorado River Between Holbrook and Winslow, Arizona", Geological Society of America Abstracts with Programs, Paper No. 26-7.

Lagasse, P.F. (1980). "An Assessment of the Response of the Rio Grande to Dam Construction – Cochiti to Isleta Reach", U.S. Army Corps of Engineers, Albuquerque, New Mexico, Technical Report, December 1980.

Lai, Yong. (2009). "Sediment Plug Prediction on the Rio Grande with SRH-2D Model". Sedimentation and River Hydraulics Group, Technical Service Center, Bureau of Reclamation, United States Department of the Interior, Denver CO.

Leopold, L.B. (1951). "Rainfall Frequency: An Aspect of Climatic Variation", American Geophysical Union Transaction, v. 32, no. 3 (June), pp 347-357.

Lettenmaier, D.P., Wood, E.F., and Wallis, J.R. (1994). "Hydro-climatological trends in the continental United States, 1948-88", Journal of Climate, v. 7, pp 586-607.

Love, D. W. (1997). "Historic incision of the middle Rio Puerco of the East: Implications for models of arroyo entrenchment and distribution of archaeological sites", in M. S. Duran and D. T. Kirkpatrick, eds., Layers of Time, Papers in honor of Robert H. Weber: Archaeological Society of New Mexico, v. 23, pp 69-84.

Makar, P., Massong, T., Bauer, T., and Oliver, K. J. (2006). "Channel Width and Flow Regime Changes along the Middle Rio Grande NM", Joint 8th FISC and 3rd FIHM Conference, Reno, Nevada.

Massong, T.M., and Porter, M D. (2004). "Changes in the Middle Rio Grande Due to the Altered Hydrology", Geological Society of America Abstracts with Programs, Denver, Colorado, Vol. 36, No. 5, p12.

Massong, T., Tashjian, P., and Makar, P. (2006). "Recent Channel Incision and Floodplain Evolution within the Middle Rio Grande, NM", Joint 8th FISC and 3rd FIHM Conference, Reno, Nevada.

Molnar, P., and Ramirez, J.A. (2001). "Recent Trends in Precipitation and Streamflow in the Rio Puerco Basin", Journal of Climate, American Meteorological Society, May 2001, Vol. 14, p 2317-2328.

Ortiz, R., and Meyer, G. (2002). "Downstream Effects of Cochiti Dam on the Middle Rio Grande, near Albuquerque, New Mexico", Geological Society of America Abstracts with Programs, Denver, Colorado, Paper No. 87-10.

Richard, G.A., and Julien, P.Y. (2003). "Dam Impacts and Restoration on an Alluvial River – Rio Grande, New Mexico", International Journal of Sediment Research, v. 18, n. 2, pp 89-96

Scurlock, D. (1998). "From the Rio to the Sierra: An Environmental History of the Middle Rio Grande Basin", U. S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, General Technical Report RMRS-GTR-5.

Tashjian, P., and Massong, T. M. (2006). "The Implications of Recent Floodplain Evolution on Habitat", Joint 8th FISC and 3rd FIHM Conference, Reno, Nevada.

Van Citters, K. (2000). "Historic Engineering Overview of the San Marcial Railroad Bridge". Submitted to U.S. Army Corps of Engineers, by Office of Contract Archeology, University of New Mexico, OCA/UNM Report No. 185-665, 63.

Wahl, K.L. (1992). "Evaluation of trends in runoff in the western United States", Proc., Managing Water Resources During Global Change, 28th Annual conf. and Symp., Reno, NV, Aver. Water Resources Association, p 701-710.